SILICON DUAL INERTIAL SENSORS

FIELD OF THE INVENTION

[0001] The present invention relates to dual inertial sensors made with micro-machining technology, including both functions of a gyroscope (angular rate sensor) and an accelerometer (acceleration sensor), and more particularly to a dual inertial sensors made with bulk-micromachining and wet etching on (110) silicon chips.

BACKGROUND OF THE INVENTION

[0002] A conventional structure of dual inertial sensors made with bulk-micromachining is shown in figure 1. It is made of (100) silicon chips 1, comprising an outer frame 2. The outer frame 2 comprises one or more inner frame 5, and each inner frame 5 is further comprising a proof-mass 3. The proof-mass 3 is connected to the inner frame 5 by a plurality of sensing flexible beams 4, and the inner frame 5 is connected to the outer frame 2 by a plurality of driving flexible beams 6. The sensing beams 4 facilitate the proof-mass 3 to move perpendicular to the surface of the silicon chip (defined as z-direction), and the driving beams 6 facilitate the proof-mass 3 to move in parallel to the surface of the silicon chip (defined as y-direction). Two glass sheets 71, 72 (not shown in figure 1) are placed on both sides of the silicon chip 1, and connected to the outer frame 2. The thin metal film electrodes 81, 82 are electro-plated on the glass sheets 71, 72 facing silicon chip surface and corresponding to the two edges of inner frame 5, respectively. The two thin metal film electrodes 81, 82, with the surface of inner frame 5, will form edge effect electrostatic driving capacitors c8p, c8n. A thin metal film electrode 9 is electrode-plated on the glass sheets 71, 72 facing silicon chip surface and the proof-mass 3. The thin metal film electrodes 9, with the surfaces of proof-mass 3, will form two sensing capacitors c9p, c9n. The alternating driving voltage on the driving capacitors c8p, c8n will make the inner frame 5 and the proof-mass 3 to vibrate along y-axis. If there is an angular velocity Ω along x-axis, there will be a Coriolis force F making the proof-mass 3 vibrate along z-axis. The angular rate can be obtained by measuring the amplitude of the z-direction vibration of the proof-mass 3. If there is an acceleration applied along the z-axis, the specific force will move the proof-mass 3 with respect to the inner frame.

The acceleration can be obtained by measuring the displacement made by the movement of proof-mass with respect to the inner frame. When the proof-mass 3 move, the capacitances of the capacitors c9p, c9n will change due to the changes in the capacitor's gap. The displacement of the proof-mass can be obtained by measuring the difference of the capacitances of the capacitors c9p, c9n. As the output signal generated by angular rate is an alternating signal, and the output signal generated by the acceleration is a low frequency or direct current signal, a signal processing method can be applied to separate the angular rate signal from the acceleration signal.

[0003] The proof-mass 3 and its sensing beams form a z-axis mass-spring vibration system. Similarly, the unit, consisting of an inner frame 5, sensing beams 4, and proof-mass 3, together with its driving beams 6, forms a y-axis mass-spring vibration system. As the amplitude of the vibration generated by the driving force of the driver is small, the resonance effect of a vibration system is used to amplify the amplitude. The amplification ratio Q is related to operating frequency and damping coefficient. The closer the operating frequency of the driver is to the resonance frequency of the vibration system, the larger the ratio Q. Similarly, the amplitude generated by the Coriolis force must rely on the resonance effect for amplification. Because the vibration frequency generated by Coriolis force is the same as that of the driving force, the resonance frequency of the sensing axis must be the same as that of the driving axis in order to generate sufficiently large output signals.

[0004] The major drawback of the aforementioned sensors is in the manufacturing process of the driving beams. As shown in figure 2, the etching is first applied on both sides of the silicon chip. As the speed of silicon wet etching is related to the lattice direction, the etching is slowest along the <111> direction. It is virtually impossible to etch along this direction. Hence, the initial stage of the etching would be as shown in figure 2(a). The slant lines represent the (111) facets. If the etching continues, it will proceeds along the <110> direction from the intersection of two (111) facets, as shown in figure 2(b). Figures 2(c)-2(e) show the side views of different stages when etching both sides of the driving beam. When the etching is perpendicular to the surface, the process should stop and the silicon chips should be removed from the etching solution. However, as there is no automatic mechanism to

stop the etching as in the (111) facet, it is hard to control the width of the driving beam. The width of the driving beam affects the coefficient of elasticity, which in turn will affect the resonance frequency. If the width of the driving beam is not accurate, the resonance frequency will be different from that of the sensing beams, and deviates from the original design. For vibration systems with larger Q values, the tolerance of the deviation is smaller. This poses major problem for the quality of the products.

SUMMARY OF THE INVENTION

[0005] The major features of the present invention are: (1) dual inertial sensors made by etching (110) silicon chip whose width can be accurately controlled during the etching process; (2) the design to reduce the air damping of the (110) silicon proof-mass; (3) preventing proof-mass from sticking to glass sheets; and (4) built-in temperature sensing capacitors placed in the chip area unaffected by the inertial force, and compensating the temperature error in the dual inertial sensors by direct measurement of the temperature changes in the chip.

[0006] The present invention will become more obvious from the following description when taken in connection with the accompanying drawings which show, for purposes of illustration only, a preferred embodiment in accordance with the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 shows the top view of a dual inertial sensors in related arts.

Figure 2 shows the etching process of the driving-beam on a (100) silicon chip in related arts.

Figure 3 shows the top view of a dual inertial sensors made with (110) silicon chip in accordance with the present invention.

Figure 4a shows the top view of the structure of an integrated driver.

Figure 4b shows stripe electrodes of the driver on glass sheet surface and their bond pads.

Figure 4c shows the cross-section view of the structure of an integrated driver.

Figure 5a shows the top view of the structure of the (110) Si chip of the preferred embodiment of the present invention.

Figure 5b shows the driving stripe electrodes pair, sensing electrodes and their bond pads on the glasses of the preferred embodiment of the present invention.

Figure 6 shows the design of stickiness prevention and the design of reducing air damping on the proof-mass.

DETAILED DESCRIPTION OF THE INVENTION

[0008] Figure 3 shows the top view of a dual inertial sensors in accordance with the present invention. Its structure is made by wet etching a (110) silicon chip 11. It is shaped as a parallelogram, instead of a rectangular shown in figure 1. The sides of all the components are in parallel with the intersection line of the (110) silicon chip surface and the silicon lattice {1-1-1} facet or {1-11} facet. Any two sides form an angle of 109.48°or 70.52°; hence most of the components are shaped as parallelograms. Because the two {111} facets, namely {1-1-1} and {1-11}, of the (110) silicon chip are perpendicular to the {110} facet, and conventional KOH and EDP etching solutions etch {111} facet much slower than {100} or {110} facets, therefore, a vertical surface can be obtained by keeping the protective mask aligned with the intersection line of the (110) silicon chip surface and the {1-1-1} facet or the {1-11} facet during the etching process. In this embodiment, the structure comprises an outer frame 2. Inside the outer frame 2 comprises an inner frame 5, and the inner frame 5 is further comprising of a proof-mass 3. The proof-mass 3 is connected to the inner frame 5 by a plurality of sensing flexible beams 4, and the inner frame 5 is connected to the outer frame 2 by a plurality of driving flexible beams 6. The sensing flexible beams 4 facilitate the proof-mass 3 to move perpendicular to the surface of the silicon chip (defined as z-direction), and the driving flexible beams 6 facilitate the inner frame 5 and the proof-mass 3 to move in parallel to the surface of the silicon chip (defined as y-direction). Two glass sheets 71, 72 (not shown in figure 3) are placed on both sides of the silicon chip 11, and connected to the outer frame 2. The thin metal film electrodes 81, 82 are electro-plated on the two glass sheets 71, 72 facing silicon chip surface and inner frame 5. The two thin metal film electrodes 81, 82 of each

glass sheet, with the corresponding surface of inner frame 5, will form edge effect electrostatic driving capacitors c8p, c8n. A thin metal film electrode 9 is electrode-plated on the glass sheets 71, 72 facing the proof-mass 3. The thin metal film electrodes 9, with the surfaces of the proof-mass 3, will form two sensing capacitors c9p, c9n. The alternating driving voltage on the driving capacitors c8p, c8n will make the inner frame 5 and the proof-mass 3 to vibrate along y-axis. If there is an angular velocity Ω along x-axis, there will be a Coriolis force F making the proof-mass 3 vibrate along z-axis. The angular rate can be obtained by measuring the amplitude of the z-direction vibration of the proof-mass 3. If there is an acceleration applied along the z-axis, the specific force will move the proof-mass 3 with respect to the inner frame. The acceleration can be obtained by measuring the displacement made by the movement of proof-mass with respect to the inner frame. When the proof-mass 3 moves, the capacitances of the capacitors c9p, c9n will change due to the changes in the distance. The displacement of the proof-mass can be obtained by measuring the difference of the capacitances of the capacitors c9p, c9n. As the output signal generated by angular rate is an alternating signal, and the output signal generated by the acceleration is a low frequency or direct current signal, a signal processing method can be applied to separate the angular rate signal from acceleration signal.

[0009] In this embodiment, the thickness of the sensing beam 4 can be controlled by the automatic etching stop of the p+ doped layer. On the other hand, the driving beam 6 is in parallel with the intersection line of the (110) silicon chip surface and the {1-1-1} facet or the {1-11} facet, hence the etching can be automatically stopped to provide the accurate width of the driving beam 6. Therefore, the difference between the resonance frequency of the driving vibration system and that of the sensing vibration system can be accurately controlled.

[0010] The driving force of the capacitor edge effect electrostatic driver is proportional to the length of the capacitor. To increase the driving force, it must increase the effective edge length. The driver can be designed in an integrated style, as shown in figure 4a. By widening the two sides 51, 52 of the inner frame 5, and etching a plurality of long trenches or slits 5t, two driving blocks 51, 52 are formed, and each trench or slit 5t can provide two edge effect drivers. The surfaces of glass

sheet 71, 72 facing the surface of the corresponding driving block 51 have two sets of long stripe electrodes 81, 82, which interpose each other, and are parallel to the long trenches or slits 5t and connected to bond-pads 81p and 81n, respectively, as shown in figure 4.b. The relative position between long trenches or slits 5t on the driving block 51, and its corresponding stripe electrodes 81, 82 is shown in the cross-sectional view in figure 4.c. Two driving capacitors c81p, c81n are formed. Similarly, the surfaces of glass sheet 71, 72 facing the corresponding driving block 52 have two sets of long stripe electrodes 81, 82, which interpose each other, and are parallel to the long trenches or slits 5t and connected to bond pad 82p and 82n, respectively. The surface of the driving block 52 and its corresponding long electrodes 81, 82 also form two driving capacitors c82p, c82n. By adjusting the phase of the external alternating voltage of the driving capacitors c81p, c81n, c82p, c82n to make the drivers exerting the force in the same direction, the driving force is increased for several times. The driving capacitors can also be used in measuring driving amplitude and to feedback for controlling driving amplitude.

[0011] Figure 5a shows a preferred embodiment of a silicon dual inertial sensors of the present invention. By combining a and b as the structure shown in figure 3, the structure is also made wet etching on a (110) silicon chip 11. This embodiment comprises an outer frame 2, which is further comprising two inner frames 5a, 5b, a central anchor 21, and a plurality of connecting masses 22. The inner frames 5a, 5b have a proof mass 3a, 3b, respectively, which is connected to the corresponding inner frame by at least a sensing resilient beam 4. Each inner frame is connected to two common connecting beams 61 by at least a driving resilient beam 6, and then connected to the central anchor 21 by the common resilient supporting beam 60. Each surface of the silicon chip, with the exception of the areas of outer frame 2, central anchor 21 and the connecting masses 22, is etched for about 3um. The sensing beams make it easier for the proof-masses 3a, 3b to move perpendicularly to the surface of silicon chip (the z-axis), and the driving beams make it easier for the inner frames 5a, 5b to move along one of the directions of the surface of the silicon chip (the y-axis). The two sides 51, 52, perpendicular to the y-axis, of the inner frames are the driving bodies, and each surface comprises a plurality of long trenches or slits 5t, perpendicular to the y-axis.

[0012] Two glass sheets 71, 72 are placed on the front side and the back side of the silicon chip 11, respectively. The glass sheets 71, 72 are combined with the outer frame 2, the central anchor 21 and the connecting mass 22. The surface of each glass sheet facing the corresponding driving body 51 has two sets of long electrodes 81, 82, which interpose each other, and are parallel to the long trenches or slits 5t and connected to bond pad 81p and 81n, respectively, as shown in figure 4.b. The relative position between long trenches or slits 5t on the driving body 51, and its corresponding long electrodes 81, 82 is shown in the cross-sectional view in figure 4.c. Two driving capacitors c81p, c81n are formed. Similarly, the surface of each glass sheet facing the corresponding driving body 52 has two sets of long electrodes 81, 82, which interpose each other, and are parallel to the long trenches or slits 5t and connected to bond pads 82p and 82n, respectively. Each surface of each driving body 52 and its corresponding long electrodes 81, 82 also form two driving capacitors c82p, c82n.

[0013] The surfaces of the glass sheets 71, 72 facing the surfaces of each proof-mass are electroplated with a metal thin film electrodes 9, which are connected to bond pads 9p, 9n, respectively, and form sensing capacitors c9p, c9n with the surfaces of each proof-mass.

[0014] By adjusting the phase of the external alternating voltages on the driving capacitors, it is possible to make the proof-mass 3a, 3b move in the opposite direction of y-axis. If there is a rotating angular speed Ω in the x-axis direction, there will be a Coriolis force to move proof-mass 3a, 3b in the opposite direction of z-axis. If an acceleration is input along the z-axis, the specific force will move the proof-mass 3a, 3b along the z-axis. When the proof-mass 3a, 3b move, the capacitance of the sensing capacitors c9p, c9n formed by the proof-mass and the metal thin film electrodes 9 on the glass sheets 71, 72 will change due to the distance change. The displacement (distance) of the proof-mass 3a, 3b can be calculated by measuring the capacitance difference between the sensing capacitors c9p, c9n. The output signal from the rotation rate is an alternating signal, and the output signal from the acceleration is a direct signal. These two signals can be separated by signal processing technology. The electrodes 9 of the sensing capacitors c9p, c9n can also be partitioned, as shown

in figure 5b, into a feedback electrode 9f, and its bond pad 9fb for the gyroscope to rebalance the Coriolis force.

[0015] To reduce the air damping due to squeeze film caused by the vibration of the proof-mass 3, 3a or 3b along the z-axis and increase the resonance amplification ratio Q of the z-axis vibration system, the surface of the proof-mass 3 can be etched to form a plurality of long trenches or slits 3t parallel to the side of the proof-mass, as shown in figure 6. Because the present invention uses (110) silicon chip, which is easy for vertical deep etching, the etching of long trenches or slits will not use a large area for sensing capacitors, and can increase the sensitivity of the output signal, as compared with the (100) silicon case. If the air resistance is still too large, it must be partially vacuumized.

[0016] To avoid the stickiness problem in the process of bonding the silicon chip and glass sheets, a plurality of small bumps or convex 3s and its insulation layer 3i can be provided on the surface of the proof-mass 3 for separator, as shown in figure 6.

[0017] To enhance the bonding force between the silicon chip and the glass sheets, the non-specific part of the silicon chip, which does not interfere with the movement of components should be kept, as the connecting block 22 in figure 5.a, to attach to the glass sheets.

[0018] To eliminate the impact of temperature on the output signals, and to improve the performance of the gyroscope and accelerometers, a small concave TS1 can be etched on the surfaces of the outer frame 2, the central anchor 21, or connecting block 22. A metal thin film electrode TS2 is electroplated on the corresponding surface of the glass sheet, and connected to bond pad TS to form a capacitor cTS for sensing temperature. Because it is affected by neither the rotation rate nor the acceleration, and only affected by the temperature, it can be used to compensate the impact of the temperature on the capacitors c9p, c9n, which are for sensing inertial force.

[0019] As shown in figure 5.a, because the silicon chip is electrically conductive, a small concave slit st must be etched on the surfaces of the outer frame 2, where the thin film metal wire passes, in order to avoid short circuit.

[0020] Based on the design of the two embodiments, there can be many different design and combination. For example, the capacitor gap between the proof-mass and the two glass sheets can be replaced by concaves etched on the surface of the glass sheets. The layout of the resilient beams can also be varied, for example, the driving resilient beam 6 of the inner frame can also be connected to outer frame 2.

[0021] In summary, the present invention disclosed a dual inertial sensors made of (110) silicon chip with vertical deep etching. The width of driving beam and the driving resonance frequency can be precisely controlled to improve the yield rate and the performance of the gyroscope. It also provides the other features: a design to reduce air resistance to improve the resonance amplification ratio of the sensing axis; a design for preventing the stickiness problem between the proof-mass and the glass sheets; and at least a built-in temperature sensing capacitor for real time measurement of temperature change in the chip to improve the temperature effect of the dual inertial sensors.

[0022] While we have shown and described the embodiment in accordance with the present invention, it should be clear to those skilled in the art that further embodiments may be made without departing from the scope of the present invention.